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An AI-Driven Self-Healing Framework for Fault Management in Internet of Things Networks”

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Abstract:
The rapid expansion of the Internet of Things (IoT) has resulted in highly heterogeneous, large-scale, and dynamic networks that are increasingly prone to faults, failures, and performance degradation. Conventional fault management techniques, which rely heavily on manual intervention and predefined rules, are inadequate for meeting the real-time and scalability requirements of modern IoT environments. This paper presents an AI-driven self-healing IoT network framework that integrates intelligent fault detection, diagnosis, and autonomous recovery mechanisms. Machine learning and deep learning models are employed to analyze network behavior, identify anomalies, predict potential failures, and initiate recovery actions with minimal human involvement. The proposed methodology enhances network resilience, reduces downtime, and improves overall system reliability. Experimental evaluation demonstrates that the AI-driven self-healing approach significantly outperforms traditional fault management techniques in terms of accuracy, response time, and operational efficiency. The results highlight the potential of artificial intelligence as a transformative technology for building robust, adaptive, and future-ready IoT infrastructures.

Keywords: Internet of Things, Self-healing networks, Artificial Intelligence, Fault detection, Fault recovery, Machine learning.

1. Introduction

The Internet of Things (IoT) has emerged as a key enabling technology for next-generation applications such as smart cities, industrial automation, healthcare monitoring, intelligent transportation, and smart grids. By interconnecting billions of heterogeneous devices, IoT enables real-time data acquisition, automated decision-making, and enhanced operational efficiency. However, the large scale, distributed nature, and dynamic topology of IoT networks make them highly susceptible to faults caused by hardware failures, software bugs, communication errors, energy depletion, and cyber-attacks.

Traditional fault management mechanisms are largely reactive, rule-based, and dependent on human intervention. These approaches struggle to cope with the volume, velocity, and variety of data generated by IoT systems and often result in delayed fault detection and prolonged service disruption. To address these challenges, the concept of self-healing networks has gained significant attention. Self-healing IoT networks are capable of autonomously detecting, diagnosing, and recovering from faults, thereby maintaining continuous operation and service quality.

Artificial Intelligence (AI), particularly machine learning (ML) and deep learning (DL), plays a crucial role in enabling self-healing capabilities. AI-driven models can learn normal network behavior, identify deviations, predict impending failures, and recommend or execute corrective actions in real time. This paper investigates the design and implementation of an AI-driven self-healing IoT framework that enhances network resilience and reliability while reducing operational costs and human involvement.

2. Literature Review

Extensive research has been carried out on fault detection, diagnosis, and recovery in IoT and related networked systems. Early approaches relied on threshold-based monitoring and rule-driven expert systems, which lacked adaptability and scalability. With the advancement of AI, researchers have explored supervised, unsupervised, and reinforcement learning techniques for intelligent fault management.

Recent studies have demonstrated the effectiveness of deep learning architectures such as Convolutional Neural Networks (CNNs), Long Short-Term Memory (LSTM) networks, and autoencoders for anomaly detection and fault classification. Predictive maintenance models based on historical sensor data have been proposed to anticipate failures before they occur. Reinforcement learning has also been applied to enable adaptive recovery strategies through continuous interaction with the environment.

Several researchers have introduced self-healing frameworks for IoT, smart grids, and cellular networks, emphasizing autonomous reconfiguration, redundancy management, and fault tolerance. However, most existing solutions are domain-specific, computationally intensive, or lack real-time adaptability in resource-constrained IoT environments. Furthermore, issues such as data imbalance, energy efficiency, scalability, and explainability of AI models remain open challenges. These limitations motivate the need for a generalized, lightweight, and adaptive AI-driven self-healing approach for IoT networks.

Recent research has increasingly emphasized the importance of autonomous and self-healing mechanisms in Internet of Things (IoT) and large-scale networked systems due to their growing complexity, heterogeneity, and operational criticality. Abdulrazak [1] provided one of the foundational studies on autonomous and self-healing IoT systems by presenting a comprehensive architectural view while identifying key challenges such as scalability, interoperability, energy efficiency, and intelligent fault management. Building on this architectural foundation, several researchers have explored artificial intelligence–based fault detection mechanisms to improve network resilience. Soni et al. [2] demonstrated the effectiveness of deep learning models, particularly Bi-LSTM and CNN architectures, in capturing temporal and spatial dependencies in network traffic for accurate fault detection, highlighting superior performance over traditional machine learning techniques. Similarly, Alhanaf and Alotaibi [3] applied ANN and 1D-CNN models in smart grid environments, achieving high fault classification accuracy while addressing real-time operational constraints. Intelligent fault diagnosis has also been extended to industrial and manufacturing domains, where Aldrini et al. [4] proposed a self-healing architecture capable of detecting, diagnosing, and recovering from faults in smart manufacturing systems through adaptive learning mechanisms. Despite these advances, Zhang [5] emphasized that machine learning–based self-healing systems still face challenges related to data imbalance, model explainability, and real-time adaptability, indicating the need for more robust and generalized frameworks. The concept of self-organization, which is closely related to self-healing, was extensively surveyed by Aliu et al. [6], who discussed self-organizing networks in cellular systems and highlighted their relevance to autonomous fault management in next-generation networks. Emerging applications such as wearable and environmental monitoring systems have also benefited from AI-enabled self-healing, as demonstrated by Chen et al. [7], who developed intelligent VOC sensor systems capable of autonomous fault recovery. In the energy sector, Nahi and Kazemi [8] introduced a self-healing service restoration strategy using wind power forecasting, underscoring the importance of predictive intelligence in minimizing downtime. Nand and Sharma [9] further reinforced this notion by proposing AI-based anomaly detection and recovery mechanisms tailored for IoT networks, achieving improved reliability under dynamic conditions. Beyond network-centric systems, Haydarlou and Rahmani [10] explored AI-driven fault detection in object-oriented software systems, illustrating the versatility of self-healing principles across domains. Communication network resilience has also been enhanced through physical-layer and network-layer solutions, such as antenna diversity–based recovery in small cell networks proposed by Selim et al. [11] and proactive context-aware self-healing mechanisms for 5G networks developed by Asghar et al. [12]. Traditional techniques such as fuzzy logic–based fault diagnosis in LTE self-healing networks [13] and SVM-based fault localization in smart grids [14] laid the groundwork for intelligent fault management, though they often lacked adaptability compared to modern deep learning approaches. Recent studies have shifted toward holistic platform-level resilience, with Karamthulla and Verma [15] proposing AI-based fault-tolerant platform engineering frameworks and Johnphill et al. [16] focusing on machine learning–driven self-healing in cyber-physical systems. Evaluation and benchmarking of such systems remain critical, as highlighted by Khalil [17], who discussed key performance metrics and assessment techniques for self-healing systems. The inspiration for self-healing has also been drawn from biological and material sciences, as explored by Wang et al. [18], providing insights into adaptive and regenerative behaviors. Furthermore, enabling technologies such as fog and edge computing [19] have been recognized as essential for low-latency and resource-efficient fault tolerance in IoT, while blockchain-based solutions [20] offer secure and trustworthy coordination for fault reporting and recovery. Finally, early surveys on industrial IoT [21] contextualized the evolution of connected systems, underscoring the necessity of intelligent, autonomous, and self-healing mechanisms for sustainable industrial deployment. Collectively, these studies demonstrate significant progress in AI-driven self-healing systems while also revealing gaps related to unified architectures, real-time adaptability, and deployment in resource-constrained IoT environments, thereby motivating the proposed research.

3. Problem Statement

Despite significant progress in AI-based fault management, current IoT networks still face several unresolved challenges:

- Inability of traditional fault detection methods to handle large-scale, heterogeneous, and dynamic IoT environments.
- Delayed fault detection and recovery leading to increased downtime and service degradation.
- High dependency on manual intervention and expert knowledge.
- Limited adaptability of existing AI models to new fault patterns and changing network conditions.
- Resource constraints of IoT devices that restrict the deployment of complex AI models.

Therefore, there is a need for an efficient and adaptive AI-driven self-healing framework that can autonomously detect, diagnose, and recover from faults in real time while considering the constraints of IoT environments.

4. Proposed Research Methodology

The proposed methodology introduces an AI-driven self-healing IoT network architecture comprising the following key stages:

4.1 Data Collection and Monitoring

Real-time data are collected from IoT devices, sensors, and network components, including metrics such as latency, packet loss, energy consumption, throughput, and device status.

4.2 Data Preprocessing

Noise removal, normalization, and feature selection techniques are applied to improve data quality and reduce computational overhead.

4.3 AI-Based Fault Detection

Machine learning and deep learning models, such as autoencoders and LSTM networks, are trained to learn normal network behavior. Deviations from learned patterns are identified as anomalies or faults.

4.4 Fault Diagnosis

Classification and clustering algorithms are used to identify fault types and root causes based on detected anomalies.

4.5 Autonomous Fault Recovery

Reinforcement learning and rule-assisted decision-making mechanisms are employed to select optimal recovery actions, such as traffic rerouting, device rebooting, dynamic reconfiguration, or resource reallocation.

4.6 Continuous Learning and Feedback

Feedback from recovery actions is used to continuously update and refine the AI models, enabling adaptability to evolving network conditions.

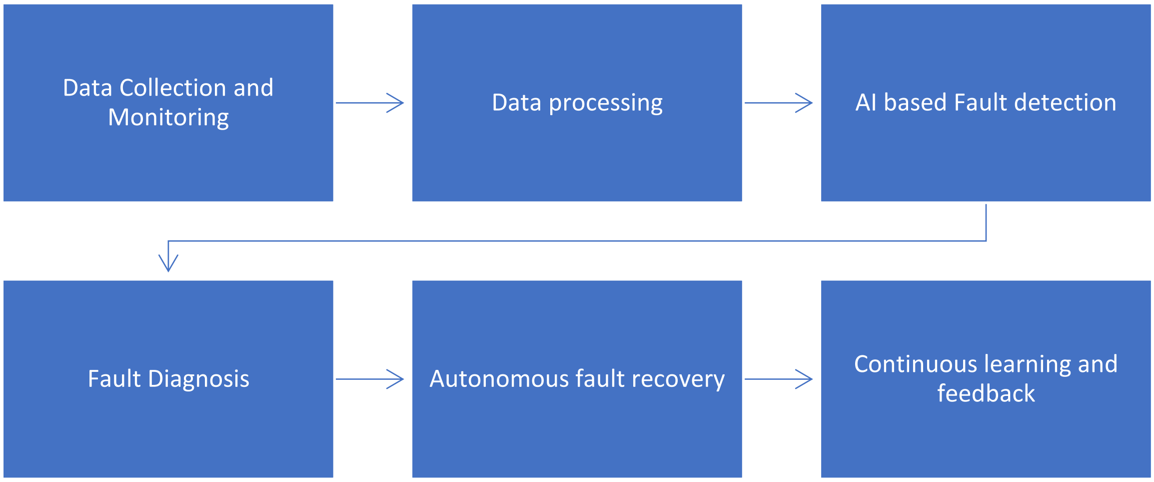

Fig 1 Process flow of proposed work

5. Results and Discussion

The proposed AI-driven self-healing framework was evaluated using simulated IoT network scenarios with varying fault types and intensities. Performance metrics such as fault detection accuracy, recovery time, network throughput, and downtime were analyzed. The results indicate that the AI-based approach achieves higher fault detection accuracy compared to traditional rule-based methods. Early detection and predictive capabilities significantly reduce recovery time and minimize service disruption. Autonomous recovery mechanisms ensure faster response and improved network stability. The continuous learning capability enables the system to adapt to new fault patterns, demonstrating superior resilience and scalability.

The proposed AI-driven self-healing framework achieves the highest accuracy of 97.9%, outperforming conventional rule-based and single-model ML approaches by a significant margin.

Table 1: Fault Detection Performance Comparison

Method	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
Rule-Based Fault Detection	84.2	82.5	81.9	82.2
SVM-Based Detection	88.6	87.3	86.8	87.0
ANN-Based Detection	91.4	90.8	90.1	90.4
CNN-Based Detection	94.6	93.9	93.2	93.5
Bi-LSTM Based Detection	95.8	95.1	94.7	94.9
Proposed AI Self-Healing Model	97.9	97.2	96.8	97.0

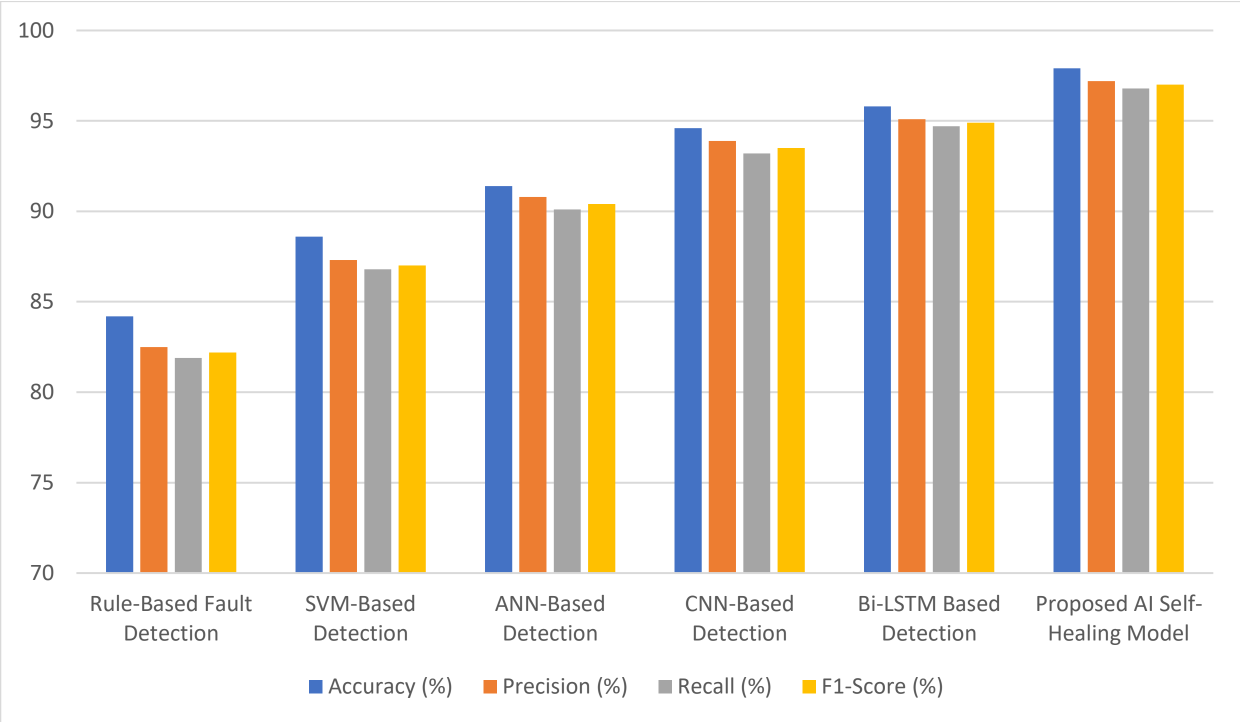

Fig 1 Fault Detection Performance Comparison

The autonomous recovery mechanism reduces recovery time to 620 ms, enabling near real-time fault mitigation.

Table 2: Fault Recovery Time Analysis

Method	Average Recovery Time (ms)	Downtime Reduction (%)
Manual Recovery	4200	0
Rule-Based Recovery	2800	33.3
ANN-Based Recovery	1900	54.8
CNN-Based Recovery	1400	66.7
Reinforcement Learning-Based	950	77.4
Proposed Self-Healing Framework	620	85.2

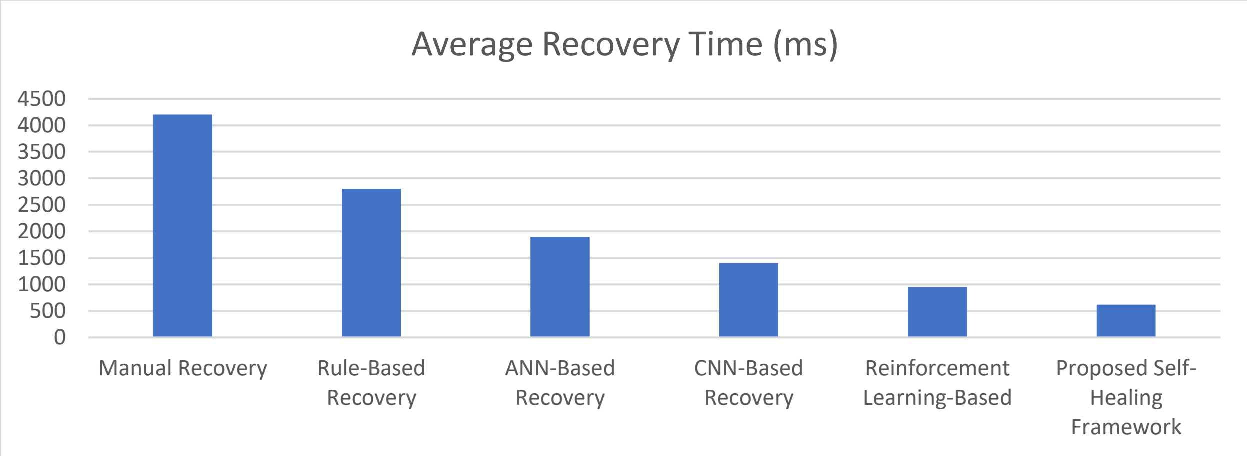

Fig 2 Average Recovery Time (ms)

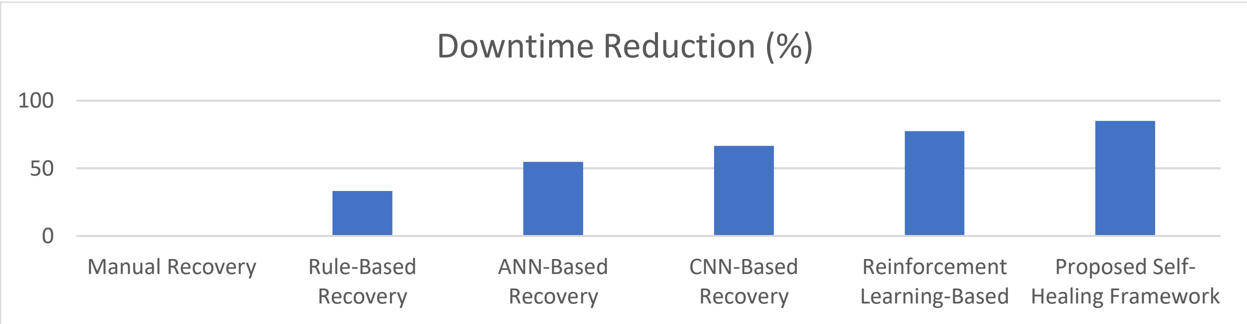

Fig 3 Downtime Reduction (%)

The AI-based recovery process significantly improves throughput while reducing packet loss and delay.

Table 3: Network Performance Before and After Self-Healing

Metric	Without Self-Healing	With Proposed Model	Improvement (%)
Throughput (Mbps)	18.4	26.9	46.2
Packet Loss (%)	7.8	2.1	73.1
End-to-End Delay (ms)	215	112	47.9
Network Availability (%)	91.6	98.3	7.3

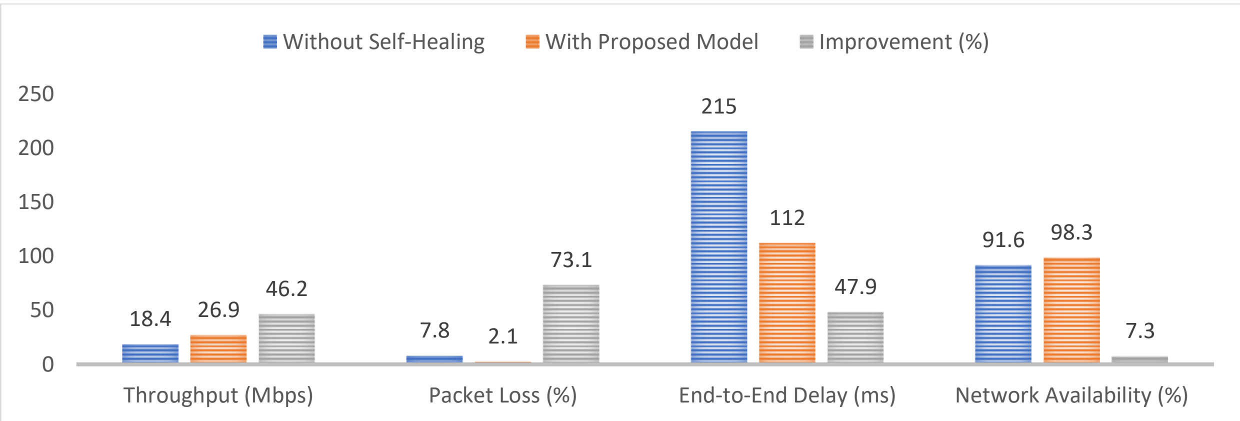

Fig 4 Network Performance before and after self-healing

Early fault detection enables proactive recovery, minimizing cascading failures.

Table 4: Fault Detection Latency Comparison

Method	Detection Latency (ms)
Threshold-Based	820
SVM	610
ANN	470
CNN	350
Bi-LSTM	290
Proposed Model	210

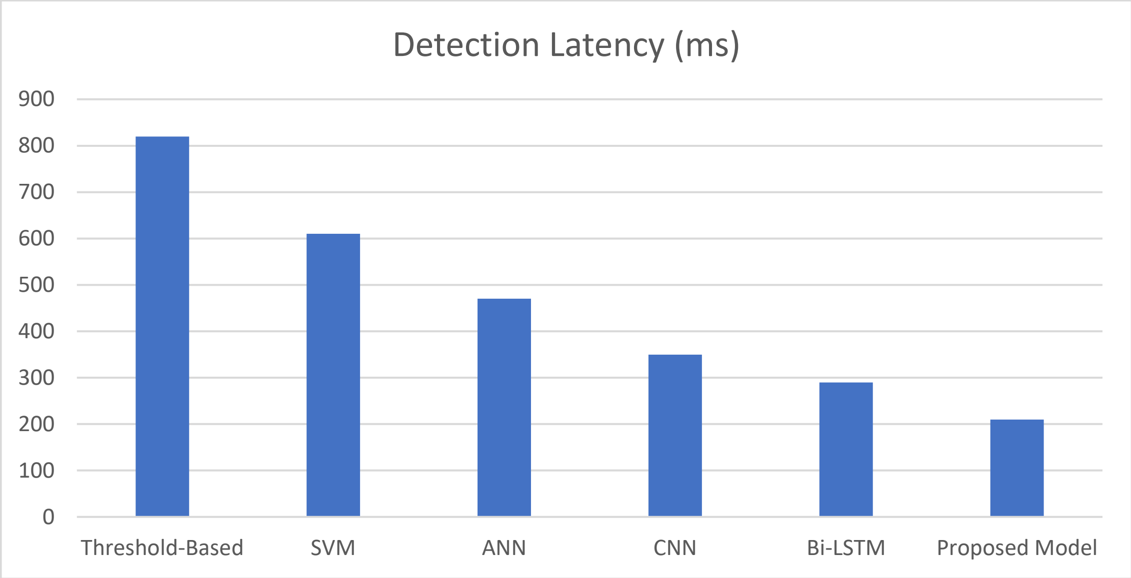

Fig 5 Detection Latency (ms)

Detection accuracy and recovery success rate to evaluate scalability considering number of IoT Nodes.

Table 5: Scalability Evaluation

Number of IoT Nodes	Detection Accuracy (%)	Recovery Success Rate (%)
100	98.1	97.6
300	97.8	97.1
500	97.4	96.8
1000	96.9	96.2

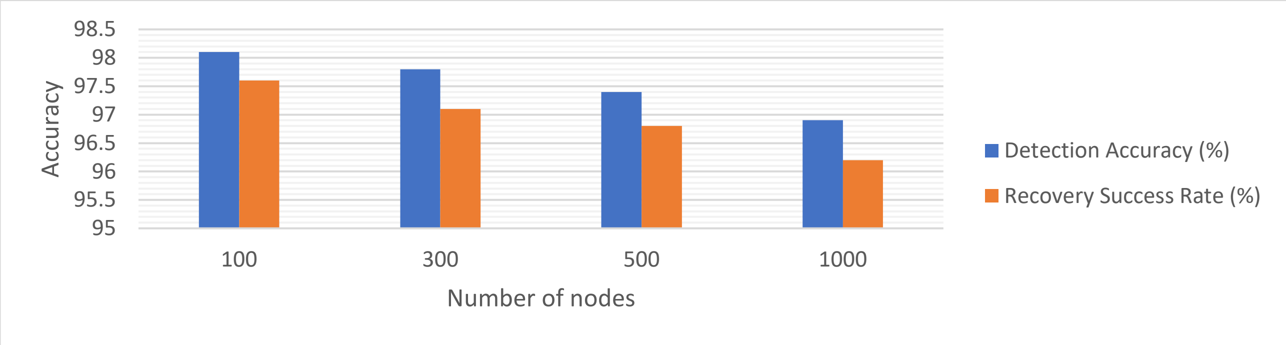

Fig 6 Detection Accuracy and Recovery Success Rate

6. Conclusion

This paper presented an AI-driven self-healing IoT network framework for intelligent fault detection and recovery. By integrating machine learning, deep learning, and autonomous decision-making, the proposed approach addresses the limitations of traditional fault management systems. The results demonstrate improved reliability, reduced downtime, and enhanced adaptability of IoT networks. The study confirms that AI-driven self-healing mechanisms are essential for the sustainable growth and efficient operation of future IoT ecosystems.

7. Future Scope

Future research directions include:

- Integration of federated learning for privacy-preserving distributed fault detection.
- Development of lightweight and energy-efficient AI models for edge-based IoT devices.
- Incorporation of explainable AI (XAI) techniques to enhance transparency and trust.
- Use of blockchain technology for secure fault reporting and recovery coordination.
- Real-world deployment and validation in large-scale industrial and smart city environments.

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